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## Research Article

# Analysis of the Influence of Microcellular Injection Molding on the Environmental Impact of an Industrial Component

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Microcellular injection molding is a process that offers numerous benefits due to the internal structure generated; thus, many applications are currently being developed in different fields, especially home appliances. In spite of the advantages, when changing the manufacturing process from conventional to microcellular injection molding, it is necessary to analyze its new mechanical properties and the environmental impact of the component. This paper presents a deep study of the environmental behavior of a manufactured component by both conventional and microcellular injection molding. Environmental impact will be evaluated performing a life cycle assessment. Functionality of the component will be also evaluated with samples obtained from manufactured components, to make sure that the mechanical requirements are fulfilled when using microcellular injection molding. For this purpose a special device has been developed to measure the flexural modulus. With a 16% weight reduction, the variation of flexural properties in the microcellular injected components is only 6.8%. Although the energy consumption of the microcellular injection process slightly increases, there is an overall reduction of the environmental burden of 14.9% in ReCiPe and 15% in carbon footprint. Therefore, MuCell technology can be considered as a green manufacturing technology for components working mainly under flexural load.

## 1. Introduction

Microcellular injection molding (MuCell) is a production process that uses a blend of melted polymer and a supercritical fluid. This blend is inserted into the barrel to create a single phase polymer-gas solution. When this solution is pushed into the cavity through the nozzle, due to the fast pressure drop, a large number of nucleation cells are formed. During filling and postfilling stages, cells growth and coalescence take place, controlled by melt pressure and temperature [1].

Microcellular injection molding offers advantages to plastic components processing. From the point of view of product quality, warpage of the component is reduced [2] due to lower shrinkage [3]. On the other hand, the surface quality may require improvement [4]. From the point of view

of the process, weight decreases due to cell generation and it allows cycle time reductions of up to 80%. Holding pressure can also be avoided due to the uniform packing caused by cells growing. This means that internal stresses of the molded component are reduced [5]. Also, the viscosity of the solution is lower than the polymer itself [6], so the required injection pressures and clamping forces are lower, allowing longer flow lengths when designing the mold.

Home appliances are one of the industrial sectors which are expected to take advantage of the characteristics of microcellular injection molding. At the moment, most plastic components are produced with conventional injection molding. However, in order to apply microcellular injection molding, manufacturers have to ensure that all the technical requirements of the components are fulfilled. Mechanical



FIGURE 1: Upper side (a) and lower side (b) of the component.

requirements are one of the most important ones for the proper functionality of a home appliance component. For that reason, the mechanical properties must be evaluated and guaranteed before proposing to use an alternative manufacturing process.

On the other hand, environmental conscience in this sector is increasing, and currently hardly any research has been carried out to evaluate the environmental impact of microcellular injection molding, comparing it with conventional injection, not only from the point of view of the process itself but also from the point of view of the whole life cycle of the final component.

As the environmental awareness increases, quantifying the environmental burden created by a component has become a key issue. The European Union has passed several laws seeking to reduce the environmental impact caused by consumer products, like the WEEE directive (waste electrical and electronic equipment) [7] or the EuP (energy-using products) directive [8]. LCA (life cycle assessment) is a scientific methodology that allows researchers to analyze the environmental impact in a systematic way, using a cradle-to-grave approach. This methodology has been used by numerous researchers to assess a wide range of products and services, from electronic boards [9] to milk production [10], including wind turbines [11, 12], plasma televisions [13], and food packaging [14].

Numerous studies have evaluated the mechanical properties of samples made out of different materials such as polyetherimide (PEI) [15], polyphenylene sulfide (PPS) [16], or polystyrene (PS) [17], among others. Also, the importance of the manufacturing process conditions is remarked by different studies: shot volume and injection speed [18], blowing agent concentration, mold, and melt temperature [19, 20]. In spite of all these evidences, hardly any study on mechanical properties has been performed with samples obtained from a home appliance component.

In this paper, the environmental impact will be evaluated for components manufactured by conventional injection molding and by microcellular injection molding. A LCA has been performed to analyze the influence of the process and how the weight reduction modifies the overall environmental

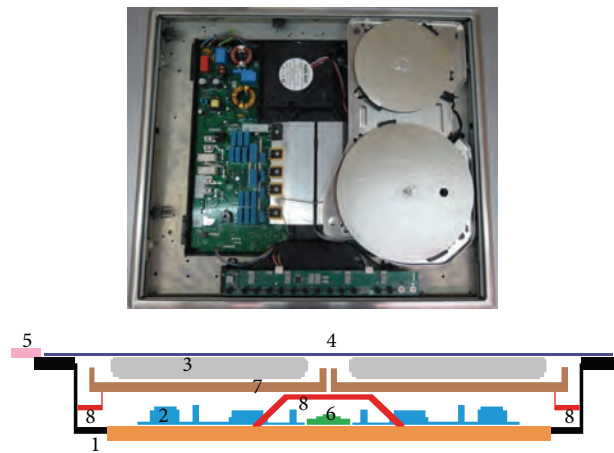


FIGURE 2: Elements of the base component assembly.

impact. As previously stated, the functionality of the component must be guaranteed, especially under flexural load, so flexural behavior will be evaluated and compared using samples obtained from manufactured components.

## 2. Materials and Methods

**2.1. Component.** The selected component is the plastic housing of an induction cooker. Figure 1(a) shows the upper side of the component where all the electronic and thermal devices are assembled onto. Figure 1(b) shows the location of the holes to screw the component to the main plate and the reinforcement of the bottom side of the component by means of a set of ribs covering the whole surface. This component works mainly under flexural load, so ribs are required to assure stiffness and avoid significant deflection. General dimensions of the component are 460 mm × 415 mm, and its general thickness is 2.5 mm.

Figure 2 shows a sectional scheme of the different devices inside an induction hob. The analyzed housing component (1) supports the electronic boards (2). The inductors (3) are in direct contact with the ceramic glass (4). A metallic frame

TABLE 1: Selected EcoInvent datasets.

Inventory data	EcoInvent dataset
Nylon 66 GF30	Nylon 6-6; glass-filled {GLO}  market for
Injection molding	Injection molding {RER}  processing
Electricity consumption	Electricity, medium voltage {ES}  market for
Truck	Transport; freight; lorry >32 metric ton; EURO4 {GLO}  market for
Disposal to landfill	Waste plastic; mixture (waste treatment) {CH}  treatment of waste plastic; mixture; sanitary landfill
Incineration	Waste plastic; mixture (waste treatment) {CH}  treatment of waste plastic; mixture; municipal incineration

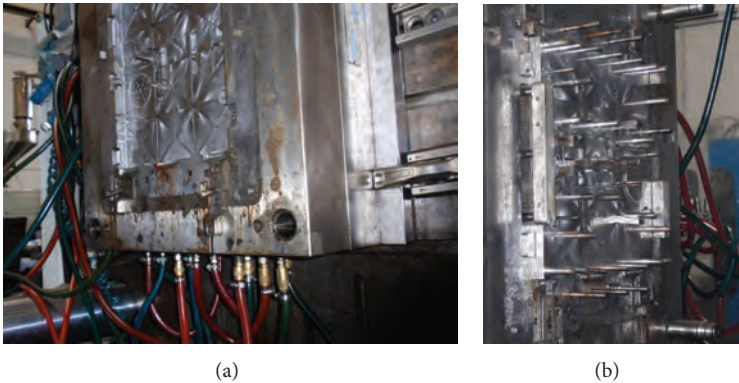


FIGURE 3: Fixed part of the mold (a) and movable part of the mold (b).

(5) closes all the assembly. A fan (6) is also supported by the housing (1). The inductors (3) are supported by an aluminum plate (7) which is placed by means of a set of springs (8).  
The mold used to manufacture the product is the same one for both conventional and microcellular injection moldings, and it is shown on Figure 3.

2.2. *Polymer Material.* The material used for this component is a PA66 reinforced with 30% of glass fiber, referenced as KELON A FR H2 CETG/300-V0 and provided by Lati Thermoplastic Industries S.p.A.

2.3. *Equipment.* For conventional injection molding a BIL-LION H6860Cl injection machine was used. Its main features are a clamping force of 750 t, 5226 cm<sup>3</sup> maximum dosage, and a screw diameter of 105 mm. For the application of MuCell technology, special equipment is required: a specific injection unit MMU (MuCell modular upgrade) which includes a special plasticizing unit, positive screw control, and a shutoff nozzle (1). The supercritical fluid used was N<sub>2</sub>, managed by a Trexel Series II SCF Delivery System, a state-of-the-art gas delivery and dosing system (2). An Automated Delivery Pressure Control System (3) is used to automatically adjust dosing conditions to assure a consistent delivery of the supercritical fluid to the polymer. N<sub>2</sub> is introduced into the melt by means of a supercritical fluid injector, placed in the rear of the barrel (4). Two antireturn valves (5) are needed along the screw before and after the location of the supercritical fluid injector (see Figure 4).

TABLE 2: Energy consumption per produced component.

Process	Consumption per produced component (Wh)
Conventional injection	653.6
MuCell	703.2

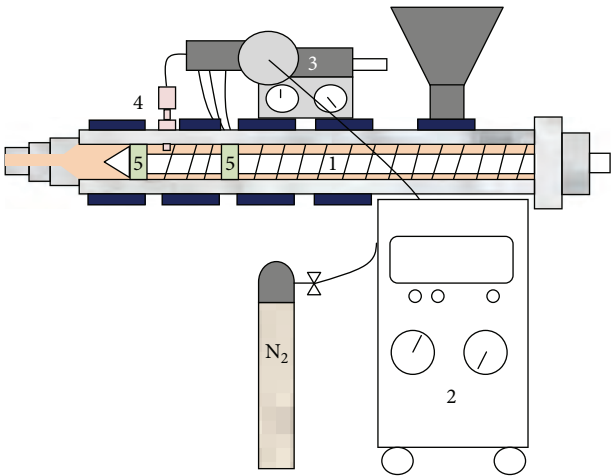


FIGURE 4: MuCell equipment.

2.4. *Processing Conditions.* Processing conditions for conventional injection molding were the ones used in the actual injection process of the manufacturer: injection temperature

TABLE 3: Environmental comparison and MuCell improvement.

Component	Weight (grams)	Recipe (mPt)	CO <sub>2</sub> footprint (Kg CO <sub>2</sub> eq.)
Conventional injection	876	628.11	7.22
MuCell	736	534.44	6.14
MuCell difference	-15.98%	-14.91%	-14.96%

TABLE 4: Detailed environmental results in ReCiPe and MuCell improvement.

Component, recipe (mPt)	Material	Process	Distribution	End-of-life
Conventional injection	532.05	64.87	18.28	12.89
MuCell	447.02	61.22	15.36	10.83
MuCell difference	-15.98%	-5.64%	-15.98%	-15.98%



FIGURE 5: Life cycle stages.

300°C, injection time 3 seconds, holding pressure 60 bars for 5 seconds, and cooling time of 7 seconds.

Processing conditions for MuCell process were chosen based on the experience of the company: injection temperature 325°C, injection time 1 second, holding pressure 180 bars for 1 second, and cooling time 4 seconds. Supercritical fluid used was N<sub>2</sub>, at a concentration of 0.4%, which allows a weight reduction of 16%. N<sub>2</sub> is injected at 200 bars and a flow rate of 1.4 Kg/hour.

For both processes, the obtained molded components did not have any visible defects and showed a stable process repeatability.

**2.5. LCA Methodology.** A life cycle assessment model has been developed to compare the environmental performance of a conventional injection molded component and of the same component using MuCell technology. The following life cycle stages have been considered: raw materials, production processes, distribution, and end-of-life (Figure 5). These components are produced in Spain and sold mainly in Europe.

The Life Cycle Inventory has been created using EcoInvent Database v3, developed by the Swiss Centre for Life Cycle Inventories. This database is currently used worldwide by more than 6000 users, in more than 40 countries. Assignment between inventory data and the databases has been carried out following EcoInvent's guidelines, as shown in Table 1.

SimaPro 8.02 has been used to calculate the LCA model using ReCiPe Endpoint (H/A) and IPCC 2007 carbon footprint. Whereas carbon footprint is highly relevant to assessing of the global warming potential, ReCiPe is a methodology that provides an endpoint indicator, which measures the overall environmental burden created by eighteen different impact categories, making the results easier and more understandable.

The functional unit is one injected housing component placed at an average consumer. This means that the influence

of the weight of the component on the transportation is also analyzed. The standard component weighs 876 grams whereas the MuCell injected weighs 736 grams (16% reduction). On average, this component travels 1800 Km by truck to arrive to the customer.

In order to analyze the environmental impact of the production process, as the energy consumption is the most relevant input, the consumptions of both injection processes, conventional and MuCell, have been measured. Using a Circutor Power Analyzer, an average consumption is obtained during stable production, as shown in Table 2.

These energy consumptions have been introduced into EcoInvent's injection dataset: "Injection molding {RER} processing," modifying the electricity consumption provided by EcoInvent and calculating the impact with the real consumptions. As the components are produced in Spain, Spanish electrical mix has been used (Table 1).

The end-of-life phase has been assessed using the guidelines provided by IEC TR 62635:2012 [21]. This type of components is treated at a WEEE plant (waste of electrical and electronic equipment). On average, filled polymers like the ones used in these components are 5% sent to valorization and 95% sent to landfill.

**2.6. Validation of the Flexural Behavior.** The function of the housing component is to locate and support all the thermal and electronic devices of the induction cooker described in Figure 2. The applied loads are the weight of all the components and the reaction force transferred to the component when the inductors are forced against the glass with the springs. These loads actuate normal to the housing, generating flexural efforts on the component. Therefore, the flexural behavior of the component will be evaluated for both conventional and microcellular injection moldings to check if there is any significant variation in flexural modulus that can affect the functionality of the component.

To evaluate the flexural modulus, the device shown in Figure 6 has been developed and used. As described in [22], a cantilever sample (1) is supported by element (2). At a distance "L" from the end of the support, a known force F is applied at the center of the cantilever sample by means of a set of weights (3). At the same point, a centesimal dial indicator



TABLE 5: Detailed environmental results in GWP and MuCell improvement.

Component, CO <sub>2</sub> (Kg eq.)	Material	Process	Distribution	End-of-life
Conventional injection	6.264	0.609	0.174	0.177
MuCell	5.263	0.586	0.147	0.149
MuCell difference	-15.98%	-3.86%	-15.98%	-15.98%

TABLE 6: Environmental results of the injection processes.

Injection process	Recipe (mPt)		CO <sub>2</sub> (Kg eq.)	
	Total	Electricity	Total	Electricity
Conventional injection	64.87	28.38	0.609	0.312
MuCell	61.22	30.53	0.586	0.336
MuCell difference	-5.64%	+7.58%	-3.86%	+7.69%

(4) is used to measure deflection. Rectangular samples cut from the component  $51 \times 10 \times 2.5$  mm were used.

When the force  $F$  is applied by (3), the time dial indicator (4) registers the deflection value  $\delta$ . Applied forces were 0.98N and 4.9N. These values have been selected in order to obtain strain values under the elastic behavior area. Five repetitions for each load were registered for samples obtained from components manufactured by conventional injection molding and MuCell technology. The methodology to calculate the flexural modulus is further described in [22].

### 3. Results and Discussion

**3.1. Environmental Impact of the Industrial Component.** After introducing the Life Cycle Inventory in SimaPro, the following results using ReCiPe and IPCC 2007 GWP (global warming potential) were obtained (Table 3).

The MuCell injected component, which weighs almost 16% less than the original component, generates a lower environmental burden both in ReCiPe (-14.91%) and in carbon footprint (-14.96%). This reduction is clearly shown in Tables 4 and 5.

The weight reduction (-16%) caused by the use of less polymer material due to the MuCell injection process reduces the environmental impact of material consumption, distribution to costumers, and end-of-life in the same amount (-16%), as those impacts are directly correlated with the weight of the components. The environmental burden created by the injected process also decreases, but by a smaller amount in both impact categories. This reduction is explained in the following section.

**3.2. Environmental Impact of the Injection Processes.** As explained in the Life Cycle Inventory, the energy consumption of both injection processes has been measured and introduced into EcoInvent's injection dataset. As there is a slight energy consumption increase per injected component in the MuCell process, the environmental burden caused by electricity consumption also increases (Table 6). On the other hand, due to the MuCell process, less material is injected, reducing the impact of the rest of inputs and outputs of the process. Overall there are small environmental impact

reductions (-5.6% in ReCiPe, -3.9% in carbon footprint) in the MuCell injection process.

**3.3. Validation of Flexural Behavior.** Table 7 shows average deflection values measured for samples under flexural load. Values of stress, strain, and flexural modulus are calculated as described in [22].

Table 7 shows that samples manufactured by MuCell have a flexural modulus only 6.8% lower than those manufactured by conventional injection molding. The weight reduction is achieved with a nonuniform material distribution through the whole cross section, due to the characteristics of MuCell microstructure (Figure 7). Larger cells usually are concentrated on the center of the section, while a thin continuous polymer skin is located at the surface of the component, as the gas diffuses out before foaming. When applying a flexural load, external layers are the most loaded; thus higher stresses are supported by the external layers, where cells have not grown. So the measured differences between MuCell and conventional injected samples for this application are small, meaning that, in this particular case, the microcellular injection molding can be used to substitute conventional molding.

### 4. Conclusions

In this paper, the influence of MuCell injection molding on the environmental impact of an industrial component with a 16% weight reduction has been studied. Although the energy consumption of the injection process slightly increases, there is an overall reduction of the environmental burden: -14.9% in ReCiPe and -15% in carbon footprint. These decreases are generated throughout every life cycle stage of the MuCell component: raw material consumption, production process, distribution to costumers, and end-of-life. In order to reassure that the MuCell injected component can be used for the same application as that of the conventional one, the influence of the microcellular injection molding on the mechanical flexural properties has been investigated using samples directly obtained from a manufactured home appliance component. A device of special purpose has been designed and developed to carry out

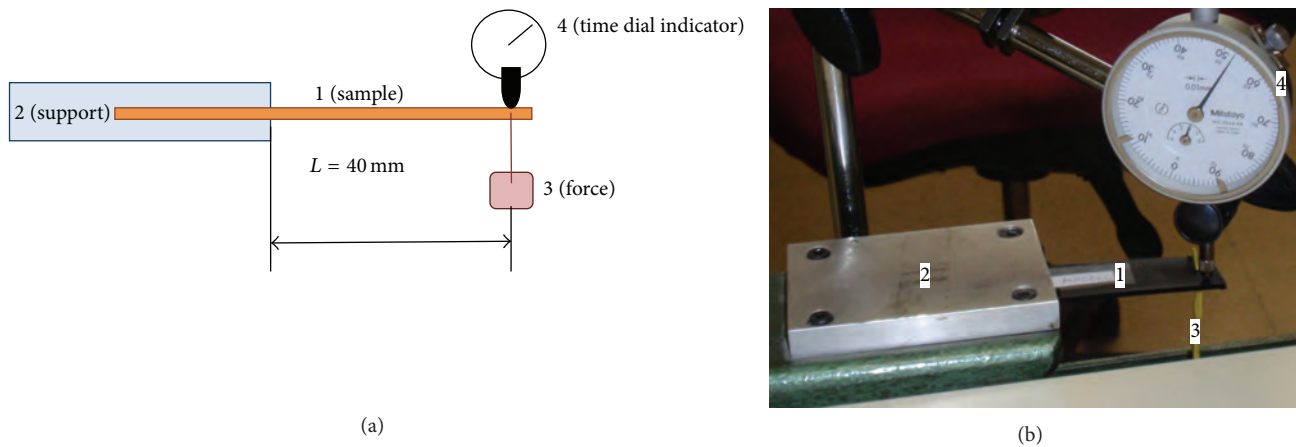


FIGURE 6: Device specially designed for flexural tests: (a) scheme and (b) real.

TABLE 7: Results of flexural test.

	$F$ (N)	$\delta$ (mm)	$\sigma$ (MPa)	$\varepsilon$	$E$ (Mpa)
Conventional injection molding	0.98	$0.26 \pm 0.005$ mm	3.76	0.0005	5947
Conventional injection molding	4.9	$1.33 \pm 0.005$ mm	18.81	0.003	
MuCell	0.98	$0.28 \pm 0.005$ mm	3.76	0.0006	5537
MuCell	4.9	$1.44 \pm 0.005$ mm	18.81	0.0033	

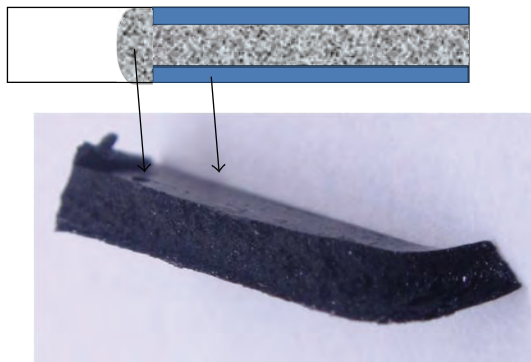


FIGURE 7: Typical MuCell structure.

the mechanical tests and evaluate results. Flexural modulus values are 6.8% lower for MuCell than for conventional injection molding. Therefore, MuCell technology is especially suited for components working mainly under flexural load.

### Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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